A MULTI-WAVELENGTH MODEL OF GALAXY FORMATION

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Abstract. We present new results from a multi-wavelength model of galaxy formation, which combines a semi-analytical treatment of the formation of galaxies within the CDM framework with a sophisticated treatment of absorption and emission of radiation by dust. We find that the model, which incorporates a top-heavy IMF in bursts, agrees well with the evolution of the rest-frame far-UV luminosity function over the range $z = 0 - 6$, with the IR number counts in all bands measured by SPITZER, and with the observed evolution of the mid-IR luminosity function for $z = 0 - 2$.

1 Introduction

We present here some recent results from a model of galaxy formation in the CDM framework which includes a sophisticated treatment of the reprocessing of starlight by dust. We use the semi-analytical model GALFORM (described in [5, 2]) to compute the masses, sizes, morphologies, gas contents, metallicities and star formation histories of galaxies. In this model, starbursts are triggered by galaxy mergers. We combine this with the spectrophotometric code GRASIL ([16]), which computes emission from stars and absorption and emission by dust, based on a 2-phase model of the ISM and a detailed physical dust grain model including PAH molecules. GRASIL computes the distribution of dust grain temperatures within each galaxy, based on a radiative transfer calculation. The output from GALFORM+GRASIL is the luminosity of each galaxy from the far-UV to the IR and sub-mm, computed self-consistently.

We used the GALFORM+GRASIL model to investigate the local universe in [8]. In [2], we investigated the star-forming Lyman-break galaxies (LBGs) and sub-mm galaxies (SMGs) at high redshift. We found that within our model, the number counts of SMGs could only be reproduced if we assumed a *top-heavy IMF* in bursts, if we required that at the same time the model reproduce the observed optical and far-IR luminosity functions at $z = 0$. Specifically, in [2], we assumed a solar neighbourhood IMF for quiescent star formation in disks, and a flat ($x = 0$) IMF for bursts. In our model, the contribution of the bursts to the total star formation density is small at $z = 0$, but dominates at high-z. In this article, we present some more predictions and comparisons with observational data based on the same model as in [2]. We concentrate here on predictions for the far-UV and IR, which are sensitive mainly to star-forming galaxies. We have presented in [9] the predictions of this model for $Ly\alpha$-emitting galaxies at high redshifts. We have also shown in [11, 12] that our (controversial!) assumption of a top-heavy IMF in bursts is supported by the chemical abundances in elliptical galaxies and in intra-cluster gas.

2 Evolution in the far-UV

Fig.1 shows the galaxy luminosity function (LF) in the rest-frame far-UV (rest-frame wavelength 1500Å) at 4 different redshifts, $z = 0, 3, 4$ and 6. The far-UV luminosity mostly traces recent star formation, but is also very sensitive to dust extinction. Comparing the solid and dashed lines in Fig.1, we see that the typical extinction at 1500Å is predicted to increase from ~ 1.5 mag at $z = 0$ to ~ 3 mag at $z = 3$. This increase in dust extinction partly offsets the brightening in the unextincted LF as one goes to higher redshift. When dust extinction is included, the far-UV LF is predicted to brighten by ~ 1 mag going from $z = 0$ to $z = 2$, and then to get fainter again at $z \gtrsim 4$. Fig.1 also shows observational data on the far-UV LF at different redshifts. The data at $z = 0$, and also that of [1] at $z = 3$, are for galaxies of all types, while the other data are only for galaxies selected by the Lyman-break technique, but this is predicted not to make much difference at high redshift. We see that when dust extinction is included, the model reproduces the observed evolution in the far-UV LF over the range $z = 0 - 6$ quite well, including the decline in the LF of LBGs from $z = 3$ to $z = 6$. Another conclusion we can draw is that the strong evolution in the dust extinction which the model predicts implies that it will be difficult to use the far-UV luminosity density by itself as an accurate tracer of the cosmic star formation history.

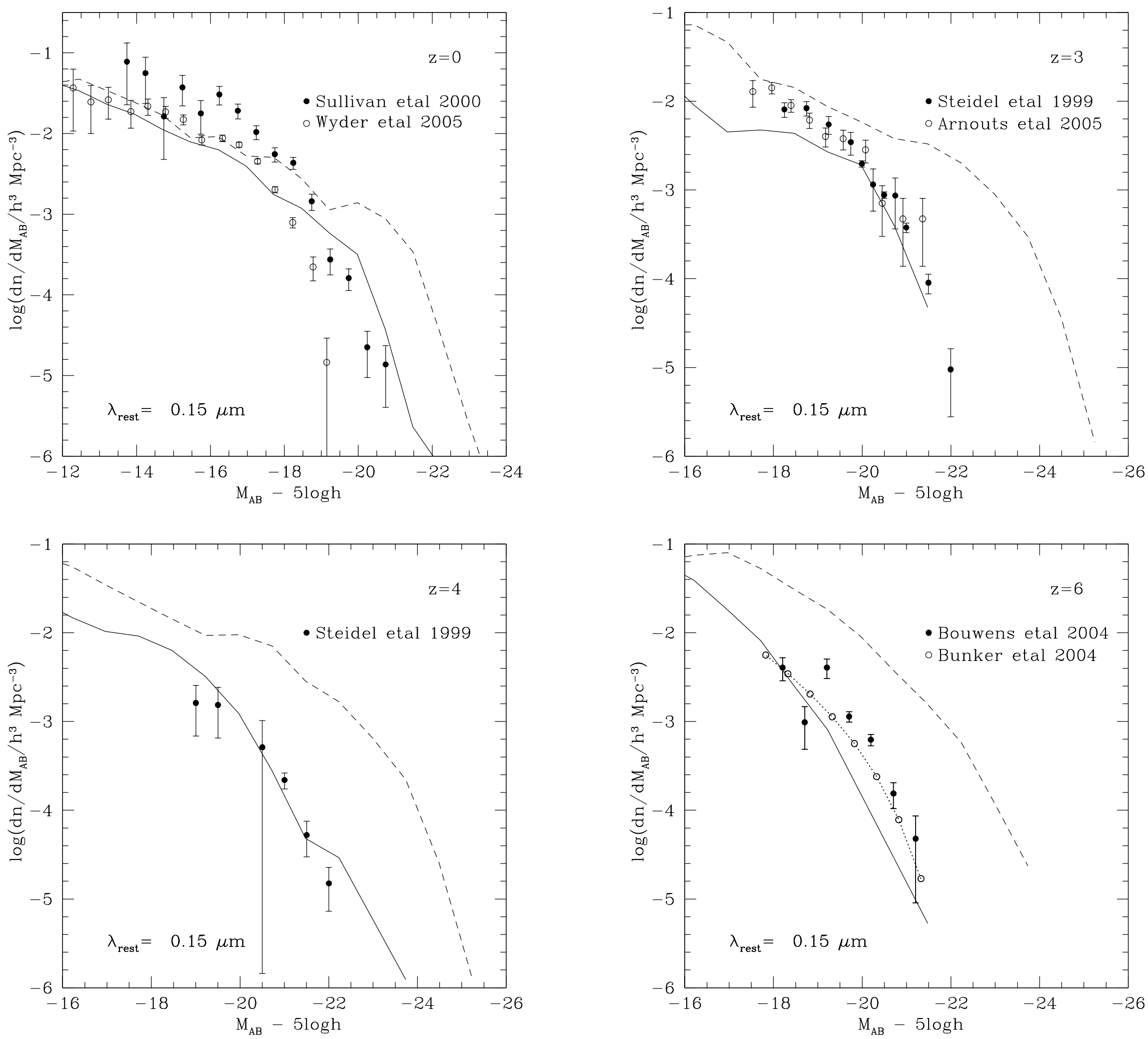

Figure 1: Evolution of the galaxy luminosity function in the rest-frame far-UV (1500Å). Each panel shows a different redshift: $z = 0, 3, 4$ and 6. The lines show the model predictions (solid: with dust extinction; dashed: no dust extinction). The points with error bars show observational data. The data of Bunker et al. at $z = 6$ are given only as a Schechter function fit, indicated by a dotted line.

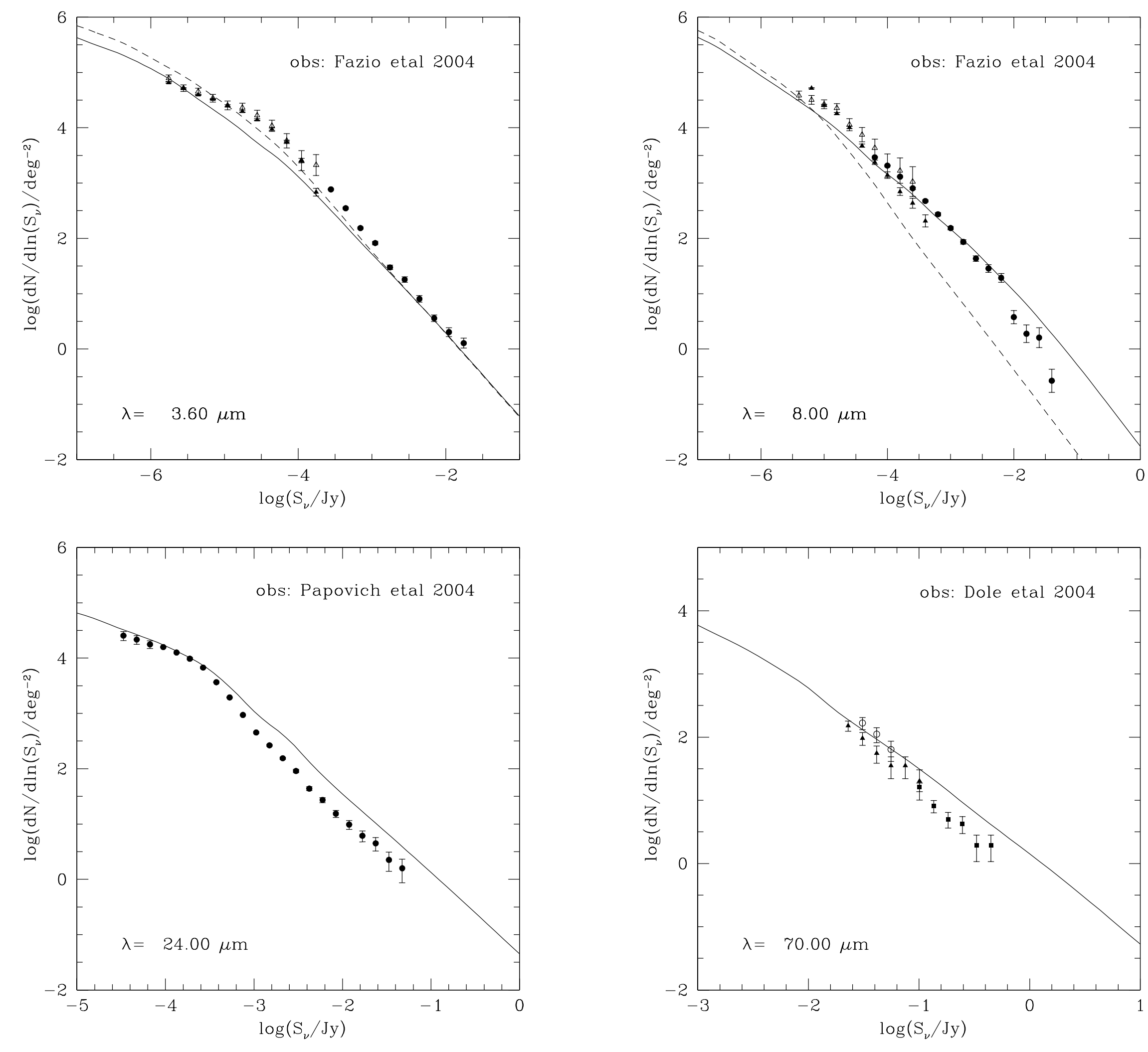

Figure 2: Galaxy number counts in the SPITZER 3.6, 8, 24 and 70 μm bands. The lines show the model predictions (solid: including dust extinction and emission; dashed: without dust). The points with error bars show observational data.

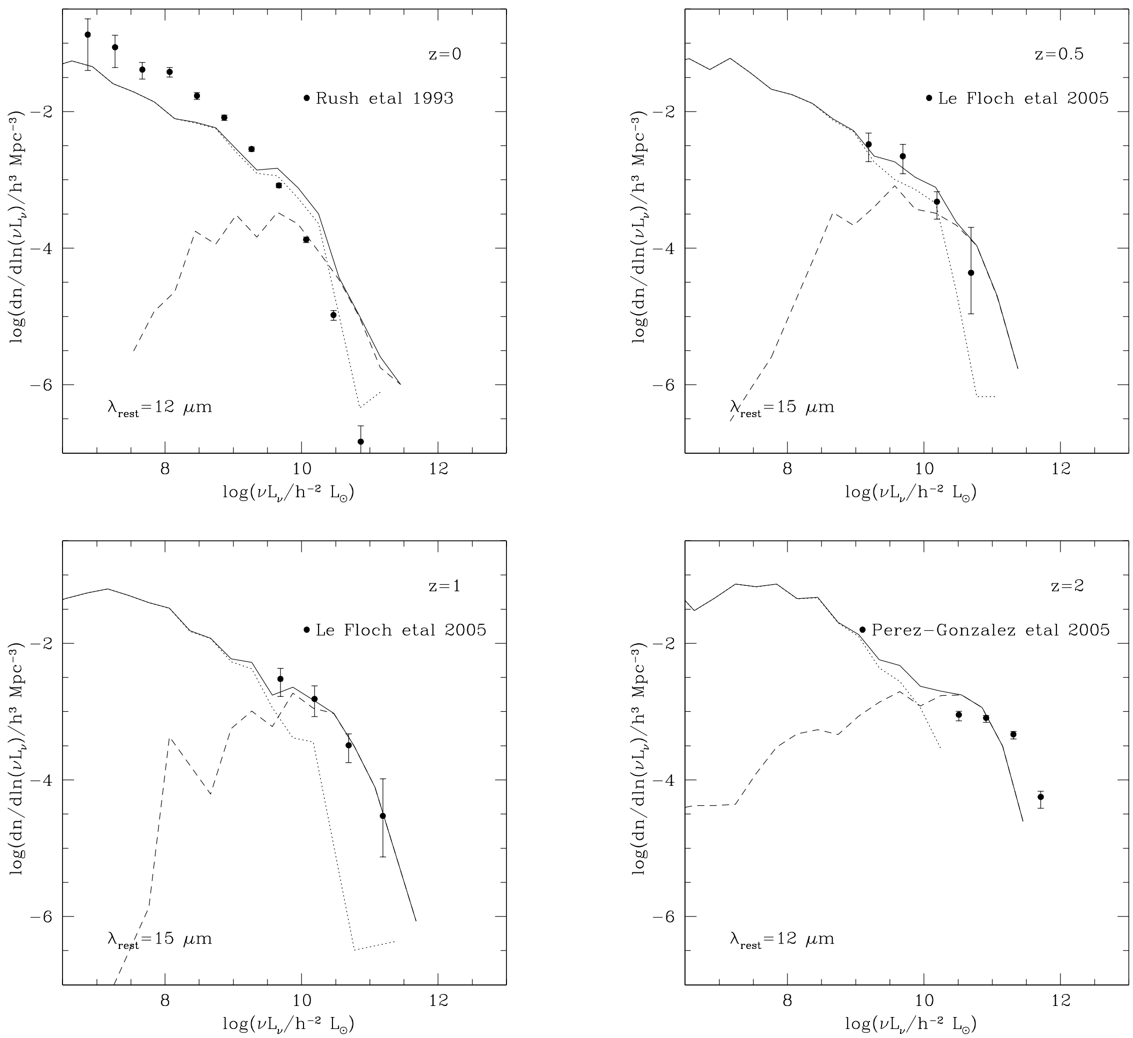

Figure 3: Evolution of the galaxy luminosity function in the mid-IR. Each panel shows a different redshift ($z = 0, 0.5, 1$ and 2), for a rest-frame wavelength of 12 or 15 μm (chosen to match the observational data for that redshift), as indicated. The lines show the model predictions (solid: total; dotted: quiescent galaxies; dashed: bursts). The symbols with error bars show observational data.

3 Evolution in the IR

In Fig.2, we show model predictions compared with observational data for galaxy number counts in the SPITZER 3.6, 8, 24 and 70 μm bands. Comparing the solid and dashed lines for the model with and without dust, we see that at 3.6μm, the counts are basically dominated by stellar emission with a small amount of dust extinction. Already at 8μm, the counts are predicted to be dominated by dust emission rather than stellar emission at brighter fluxes. At 24 and 70 μm, dust emission completely dominates. The predicted fluxes at 8 and 24 μm are very sensitive to the predicted distribution of dust temperatures within each galaxy, and to the treatment of PAH molecules. We see that the number counts predicted by the model are in quite good agreement with the SPITZER data, including the 8 and 24 μm bands.

In Fig.3, we show the galaxy luminosity function in the mid-IR (12-15μm) at 4 different redshifts, $z = 0, 0.5, 1$ and 2. For the model, we show both the total LF (solid lines) and also the separate contributions of bursts (dashed lines) and quiescent galaxies (dotted lines), from which it can be seen that the contribution of the bursts becomes increasingly important with increasing redshift. The mid-IR LF is predicted to brighten by a factor ~ 10 going from $z = 0$ to $z = 2$, and then to decline again at $z \gtrsim 4$. The total IR luminosity from dust (integrated over the range 8-1000μm) is predicted to evolve in a very similar way. Ideally, one would compare the evolution of the total IR LF predicted by the model with observational data. This would in principle provide a more robust test of the predicted star formation rates than comparing with only the mid-IR LF, since the total IR dust luminosity is independent of the details of the dust emissivity and temperature distribution, both of which affect the spectrum of the dust emission, and thus the fraction of the total IR luminosity which is seen in mid-IR bands. However, current observational data do not yet sample the IR spectral energy distributions of high-z galaxies well enough to allow model-independent estimates of their total IR dust luminosities. On the other hand, SPITZER observations at 24μm do allow a direct estimate of the evolution of the LF in the mid-IR (see [10, 14]). In Fig.3, we compare the model predictions with these SPITZER estimates, and also with data from IRAS at $z = 0$. We see that the model reproduces the observed evolution of the mid-IR LF quite well over the range $z = 0 - 2$. We note that the evolution in the mid-IR is predicted to be much weaker in our model if we drop the assumption of a top-heavy IMF in bursts, and instead assume a solar neighbourhood IMF for all star formation. In that case, the mid-IR LF brightens by only a factor ~ 3 from $z = 0$ to $z = 2$ (in disagreement with the SPITZER data), instead of the factor ~ 10 we find with a top-heavy IMF in bursts. The evolution of the LF in the mid-IR thus provides further support for our assumption of a top-heavy IMF, originally invoked to explain the number counts of sub-mm galaxies at $z \sim 2$.

4 Conclusions

We see that a galaxy formation model based on CDM, and assuming a top-heavy IMF in bursts, can explain quite well the observed evolution of star-forming galaxies seen in the UV, IR and sub-mm over the redshift range $z = 0 - 6$. Important issues remain open however, such as the evolution of more quiescent galaxies seen in the optical and near-IR, and of the stellar mass function of galaxies. We will address these issues in future work.

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